Chapter 10

Metal Ore Extraction and Processing

10.1 OVERVIEW

The industrial sequence diagram for the metal ore extraction and processing sector is shown in Figure 10.1. This sector is one of several involved in the earliest stages of the industrial materials cycle. The sector activities comprise the following: physical extraction of metal ores (mineral aggregates from which metals can be recovered) from their natural reservoirs, concentration of the desired metal by minimizing associated but unwanted ore constituents, separation of the metal atoms from the compounds in which they occur, and purification of the resulting metals.

10.2 PHYSICAL AND CHEMICAL OPERATIONS

10.2.1 The Extraction Process

In modern metal ore extraction, the most common technique is *open-pit mining*. In much the same manner as open-pit coal extraction, soils and vegetation are first removed from the mine site. Bulk ore is then extracted by blasting charges to loosen the bedrock. For less dense geological formations, special saws and drills can be used to remove the ore from the formation. The ore is then transferred to processing stations, described below. Massive industrial machinery is often used to extract and transfer the ore from the earth. As with coal mining, open-pit mining is usually cheaper and safer than the alternatives, but is less desirable from an environmental standpoint in that it generates more waste and may use more energy.

The historical (and usual) option to open-pit ore mining is *underground mining*, in which shafts are sunk into the ore deposit, passages opened off the shaft, and the ore then broken up and brought to the surface. This process is typical for vein deposits,

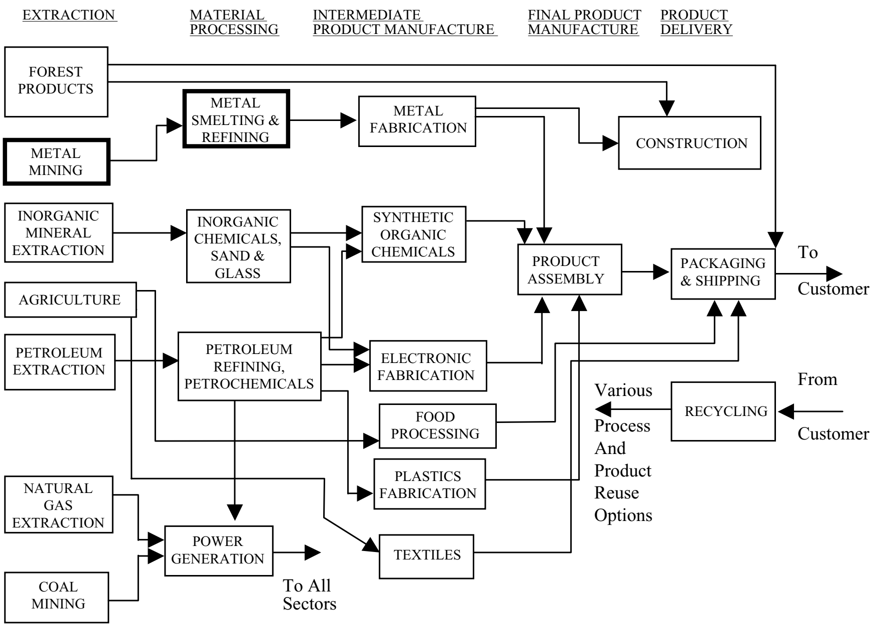

Figure 10.1. The technological sequence diagram for the metal ore extraction and processing industries. The industry sector itself is indicated by heavy outlining.

where a continuous but localized metals-rich ore vein can be followed great distances through the earth. Underground mining is often the more cost-effective option in formations where a few metals-rich veins or regions occur; open-pit mining may be the preferable method when a more expansive body of less-rich, but more voluminous, ore exists. Since the overburden is left in place during underground mining, it does not have to be dealt with, and local vegetation and habitat suffers minimal disruption. Expense and safety are often compromised, however.

The third option is *fluid mining*, in which a leaching solution is injected into drill holes to dissolve metals, and then recovered and the metal separated from the solution. This approach is not common for most of the widely-used industrial metals (e.g., iron, copper, zinc), but is much more widespread with gold and sometimes with silver.

10.2.2 *Beneficiation*

Beneficiation immediately follows extraction. The goal of beneficiation is to convert the ore into a more uniform size and higher grade than the raw material that comes from the earth after extraction. The beneficiation process typically involves two steps. The first step is *comminution* (a term synonymous with *milling*), in which the lumps of

mined ore are reduced in size by crushing and grinding processes. The usual target size is similar to the grain size of the mineral being recovered (roughly a millimeter), so several stages of size reduction are usually involved. Various preliminary purification processes may then be performed, in which metal ores are separated from unwanted materials on the basis of differential magnetic, density (the flotation process), or chemical properties. The desired ores are then commonly reduced in size by *sintering*, in which they are heated to temperatures as high as 1300°C to agglomerate and weld the particles together. Metals can then be recovered from the sintered ore, as described below.

10.2.3 Recovering the Metal from the Ore

With few exceptions, pure metals are not found in nature. Rather, they are nearly always present in either oxide or sulfide forms, shown in Table 10.1. In order to recover the metal from the ore, the bonds between the metal atoms and the sulfur or oxygen atoms must be broken, the sulfur or oxygen discarded, and the resulting metal purified. Very high temperatures are typically required to accomplish these processes.

After the ore has gone through beneficiation, metals can either be separated at a smelting facility close to the mine itself, or the beneficiated ore can be transported (usually by rail or barge) to a central location for metals recovery.

The first step in the recovery process for most metals is *smelting*, in which the ore is heated to liquefy the mineral, the chalcocide (the oxygen or sulfur) extracted in gaseous or other form, and the resulting metal skimmed off (drossed) or poured off and formed into solid bricks (ingots). Since the target metal is usually present in the *beneficiated* ore in concentrations significantly less than a few percent, a very large amount of material must be heated up and processed, and most of the accompanying material discarded.

Smelting is followed by *refining*, in which the impure ingots are reheated with various additives that scavenge impurities. The resulting slag, or waste, is skimmed off or otherwise removed, leaving the purified metal. Depending on the purity desired, several stages of refining or other purification processes may be employed.

Table 10.1. Common Forms of Metal Minerals

Metal	Mineral	Mineral Name
Aluminum	Al_2O_3	Bauxite
Copper	Cu_2S	Chalcocite
Iron	Fe_2O_3	Hematite
Lead	PbS	Galena
Silver	Ag_2S	Argentite
Zinc	ZnS	Sphalerite

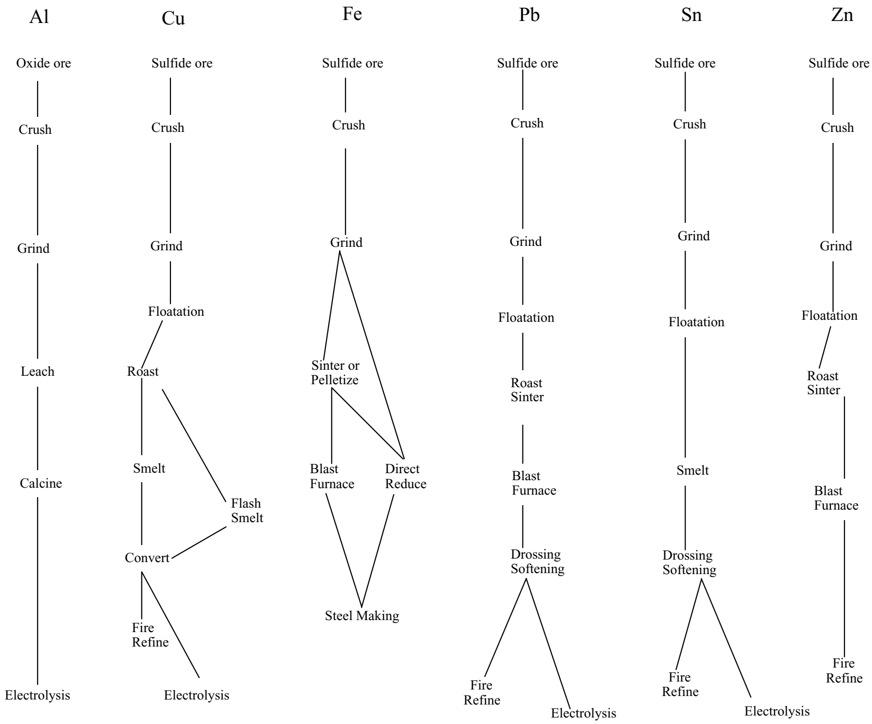

Figure 10.2. Sequences of extraction and refining for the common industrial metals. (Adapted from C. Bodsworth, *The Extraction and Refining of Metals*, Boca Raton, FL: CRC Press, 1994.)

10.2.4 Processing Sequences for the Common Industrial Metals

With some variations, almost all of the common industrial metals undergo the steps outlined above as they proceed through their transition from being part of Earth's crust to being employed as a constituent in our modern technological society. The sequences are shown in broad outline in Figure 10.2.

In the case of iron, by far the most widely mined and used of the metals, the most common process is rather different from those for other ores. It begins, as shown in Figure 10.3, with the injection of iron ore pellets, crushed limestone, and coke into a blast furnace. The coke provides the fuel for the furnace and the limestone reacts with and removes unwanted ore constituents. The molten iron that is produced is combined with other materials to generate a mixture appropriate for the type of steel desired (steel is an alloy of other constituents with iron). The *mild steels*, used for most structural and engineering purposes, contain 0.15 to 0.25 percent carbon. *High carbon steels* contain 0.6–0.7 percent carbon, and are used for more demanding applications. Specialty steels contain precise amounts of additives other than carbon.

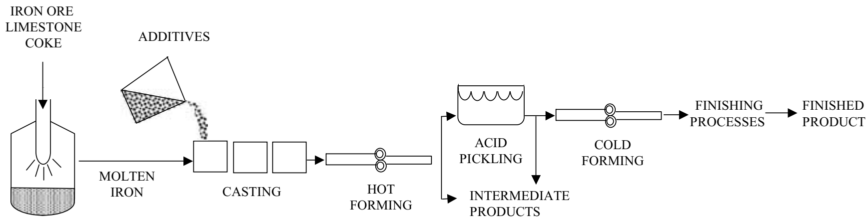

Figure 10.3. The transformation of iron ore into steel products. (a) Processing of iron ore. (b) Manufacture of steel ingots.

The most common are stainless steels, with several percent each of chromium and nickel, and high-strength steels which incorporate magnesium, silicon, tungsten, and or vanadium. The right side of Figure 10.3 outlines the casting, forming, and finishing process sequence. Some of the products, such as welded pipe, are used directly by customers. Others are provided to metal fabricators (Chapter 17), who manufacture more complex products.

The primary steel industry underwent a transition in the 1990s from using mainly blast furnace procedures to using the electric arc furnace (EAF). Steel production using EAFs is scrap-based. With the growth in use of EAFs, a great deal of ore-based steel production was shut down. This shift from ore-based to scrap-based steel has increased the recycling value of scrap steel and has decreased iron extraction pressures.

Text Box 10.1

American Scrap Metal Feeds China's Growing Steel Industry

America's scrap metal is helping to feed China's building boom. Imported scrap steel and copper is being used to build skyscrapers, factories, and telecommunications infrastructure throughout China. Reflecting a sharp rise in demand for scrap metal, the price of scrap steel soared in the first months of 2004, reaching more than $300 per ton in March, roughly double the price at the end of 2003, and up significantly from the price of $77 commanded in the beginning of 2001. Exports of scrap steel from the U.S. almost doubled between 2000 and 2004, with 30 percent of it going to China. The fraction of U.S. scrap steel exported to China remains low compared to that consumed domestically; the U.S. still consumes about seven times the amount shipped to China, although the quantity has fallen in recent years. As long as the cost of producing metal from scrap remains lower that that of producing it from ore, the scrap metal trade will remain strong.

Source: Pollack, A. and Bradsher, K. 2004. "China's need for metal keeps U.S. scrap dealers scrounging." New York Times. March 13, 2004.

The most significant difference between ferrous and non-ferrous processing (iron and steels are the *ferrous* metals, others are termed *non-ferrous*) is that the latter commonly undergo *electrolysis* as the final purification step. An electrolytic process is one in which an electric current is passed through a molten solution, and the solution constituents are differentially collected on the electrodes on the basis of their electrical charge.

The process for aluminum illustrates several characteristics of non-ferrous processes. After the ore is crushed and ground to suitable size, it still contains 10–30 percent of impurities, chiefly iron oxide. The impurities are largely removed by *leaching* the ore, i.e., by dissolving either the target material or the impurities in a chemical solution. In the case of aluminum, the solution is of sodium hydroxide (NaOH), a highly caustic chemical, and the $Al(OH)_3$ is converted to soluble $AlO \cdot ONa$. This solution is then separated from the impurities and cooled to precipitate $Al(OH)_3$. The $Al(OH)_3$ is then heated to 1200°C, upon which it is transformed to alumina (Al_2O_3), a process termed *calcining.* Finally, the alumina is dissolved in molten cryolite (Na_3AlF) at 1000°C and a large amount of electrical power applied (Figure 10.4). The dissolved aluminum ions pick up electrons at the cathode and are transformed into elemental aluminum, which sinks through the cryolite and is extracted from the bottom of the electrolytic cell.

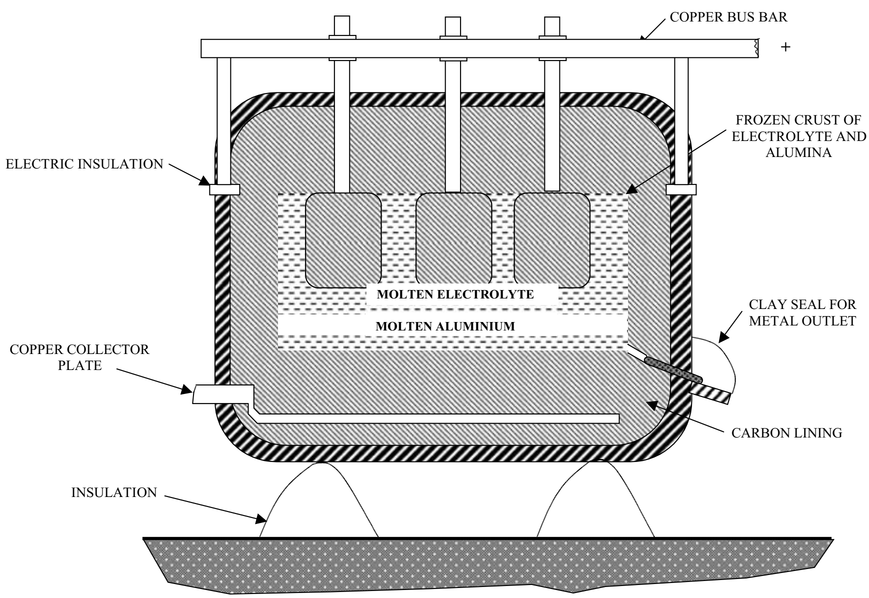

Figure 10.4. The electrolytic cell used in the production of aluminum. (Reprinted with permission from R. N. Shreve, *The Chemical Process Industries*, 2nd ed., New York: McGraw-Hill, 1956.)

Although other non-ferrous metals have lower melting points than aluminum, and can therefore be processed at somewhat lower temperatures, the same process steps tend to be used: crushing, grinding, concentration by flotation or other means, smelting, refining, and electrolytic purification. Temperatures of several hundred to a thousand degrees Celsius are typically required.

A further complication is that geological processes often deposit chemically-similar metals together. Thus, arsenic is often found in copper ores, cadmium in zinc ores, and so forth. Beneficiation, smelting, and refining must therefore deal with several metals at once, from both processing and residue standpoints.

10.3 THE SECTOR'S USE OF RESOURCES

10.3.1 Energy

The extraction and processing of metals are very energy-intensive processes, particularly in the comminution, smelting, and refining stages. In 1992, the U.S. mining industry used 8.1×10^{16} J for the extractive processing of nonferrous metals and 6.1×10^{17} J for excavating and hauling. As an industrial sector, metal ore extraction and processing ranks third in energy use behind fossil fuel extraction and the chemical industry.

Because of intrinsic differences in bond strength, melting temperatures, and other properties, the metals differ substantially in the amount of energy required to produce the same amount of material. This "embedded energy" has been analyzed by Manfred Schuckert of the University of Stuttgart. His research has resulted in quantifying the typical amount of energy needed to produce a certain amount of the target metal. As Figure 10.5 demonstrates, this amount can vary dramatically. Titanium, which has a very high melting point and is relatively difficult to purify, has an *embedded energy* of more than 260 MJ/kg. Lead, which has a very low melting point and is relatively easy to purify, has an embedded energy of only 20 MJ/kg. The concept of embedded energy is particularly important from a recycling standpoint. If we discard a kilogram of titanium, for example, we not only discard a material that we might be able to reuse, we also, in effect, discard the product of the fossil fuels that generated 260 MJ of energy. Every discard of a processed material thus has impacts on the energy cycle as well as on the cycle of the material itself.

10.3.2 Materials

Mass flows in the U.S. iron and steel industry are very large and have several characteristics worth noting. First, the amount of material that emerges from the blast furnace step is typically less than the amount lost to the environment in all forms—gases, water, slag, etc. Second, scrap input to the furnaces is large; in the case of iron production the scrap input is greater than that of virgin metal. Third, large

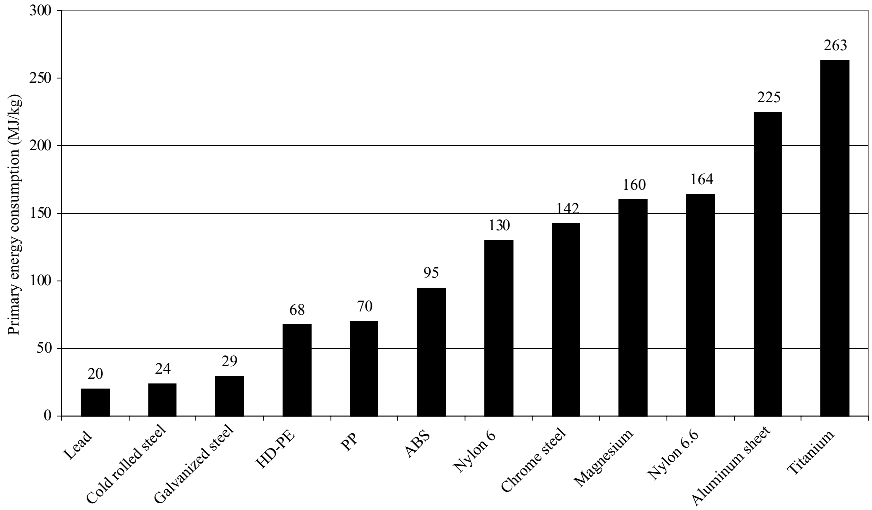

Figure 10.5. The energy embedded in metals by their manufacture. (Adapted from M. Schuckert, *Proc. 3rd Intl. Conf. on Ecomaterials*, Tokyo: Society of Non-Traditional Technology, pp. 325–329, 1997.)

Table 10.2. Depletion Times for the Common Industrial Metals

				Depletion Time (Years)	
Metal	Usage	Reserves	Reserve Base	t_D [Res] (yr)	t_D[Res Base] (yr)
Aluminum	105 Pg/yr	23 Eg	28 Eg	220	270
Copper	8.9 Pg/yr	310 Pg	590 Pg	35	66
Iron	850 Tg/yr	150 Pg	230 Pg	180	270
Lead	3.2 Pg/yr	63 Pg	130 Pg	20	41
Silver	14 Tg/yr	280 Tg	420 Tg	21	30
Tin	200 Tg/yr	8 Pg	10 Pg	40	50
Zinc	7.4 Pg/yr	140 Pg	330 Pg	19	45

*Abstracted from S. E. Kesler, *Mineral Resources, Economics and the Environment*, New York: Macmillan, pp. 347–359, 1994.

quantities of carbon dioxide are generated, making this sector a significant contributor to the global climate change problem.

As was done in Chapter 9 for fossil fuel resources, estimates of depletion times for metal resources can be calculated. The results appear in Table 10.2 where we have purposely performed the calculation using both the reserve base and the reserves. In the cases of aluminum and iron, the reservoirs of suitable minerals appear sufficient for centuries to come. For the other metals, however, reserves are much less abundant; all

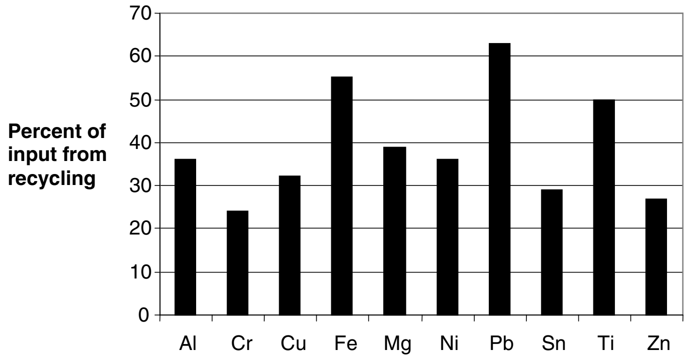

Figure 10.6. Recycled metals as a percent of total supply. (*Data source:* U.S. Geological Survey, Resources–Metals, http://minerals.usgs.gov/minerals/pubs/commodity/recycle/recymyb01.pdf, accessed August 30, 2003.)

those listed being less than 50 years on the basis of known reserves. The utilization of the currently uneconomical reserve bases of the metals would extend those depletion times by perhaps a factor of 1.5, but it appears prudent to begin thinking about vigorous conservation measures for those resources with very short depletion times such as lead, silver, and zinc.

One way in which depletion times can be lengthened is by procuring some of the needed materials though recycling rather than from virgin ores. For some metals, as shown in Figure 10.6, a significant percentage of the supply is being provided in this way. The feasibility with which metals can be recycled varies widely with the ease of recovery after first use and the suitability of reprocessing technologies, but recycling percentages continue to increase for most materials.

For the United States, the consumption, recycling, and dominant uses of the major metals are indicated in Table 10.3. It is notable that iron is both used and recycled at much higher rates than the other metals. Also of significance are the low recycling rates of both zinc and copper in comparison to the relatively low projected depletion times for these metals.

10.3.3 Process Chemicals and Ore Residues

The metal extraction process involves chemical steps as well as physical ones, and the chemicals used tend to be very aggressive. Those of greatest environmental concern are employed in leaching impurities from the ore. Perhaps the most problematic is cyanide (a solution of either KCN or NaCN), used for leaching gold from gold-bearing ores and in some lead and zinc mining processes. In a typical application, the ore is immersed in the leaching solution for periods of up to several months, after which the solution must be recovered and chemically treated if environmental damage is not to occur.

Table 10.3. Annual Flows and Major Uses of Industrial Metals in the United States (1996)

Metal	Annual Use (Tg)	Amt. Recycled (Tg)	Major Uses
Aluminum	6.3	3.1	Transportation-32% Packaging-28% Buildings-15%
Copper	2.8	0.4	Buildings-40% Electrical-25% Transportation-13%
Iron	9300	3300	Buildings-70% Infrastructure-12% Transportation-11%
Lead	1.4	1.0	Batteries-84% Paints, glass-5% Ammunition-5%
Silver	0.22	0.20	Photography-50% Electrical-20% Jewelry-10%
Tin			Solder 41% Chemicals 14% Plating 21%
Zinc	1.5	0.4	Galvanizing-55% Alloy products-31%

Source: Minerals Yearbook, U.S. Geological Survey, Washington, D.C., 1997.

Other hazardous leaching chemicals include sodium hydroxide and a variety of strong mineral acids. The byproduct of the leaching and beneficiation is *tailings*, a slurry that is typically half-liquid, half-solid, and contains extraneous crushed rock, trace metals, and residues of the chemical leaching process. In modern mining, tailings are stored in lined holding ponds; traditional practice had been to simply discard them into the nearest body of water.

Overall, the residues generated by this sector are quite high, second only to the chemical industry. Most of the material is concentration wastes (ore residues plus process chemical residues). The residues from iron and steel processing are largely ore impurities, while those from nonferrous metals processing contain substantial quantities of process chemicals or their products.

10.3.4 Water

Water use in this sector is high, as a significant amount of early-stage ore processing involves crushing of the rock followed by gravitational separation in flowing water.

Water-based separation technology tends to be inexpensive and reasonably effective, but it also implicitly degrades the local water discharge streams. The recycling and reuse of water in this sector have advanced greatly in recent years, and water use is of lesser concern thas was formerly the case.

10.4 POTENTIAL ENVIRONMENTAL CONCERNS

The metal ore extraction and processing sector has a number of potential environmental interactions. Of the top 20 chemicals or chemical groups reported under the U.S. Toxic Release Inventory for 1998, five are metal-related: zinc compounds (#2 in terms of releases and transfers), manganese compounds (#9), copper compounds (#14), chromium compounds (#18), and lead compounds (#20).

10.4.1 Solids

The principal reason that this sector uses so much energy and generates such a large quantity of solid residue is that the typical concentration of target metals in the ores is rather low. The remaining essentially valueless rocks and minerals, termed gangue, must be extracted with the target metal, separated from it, and then returned to the ground in an environmentally sound manner. The sheer quantities of material involved make this difficult. As Table 10.4 demonstrates, of the ore mined worldwide in 1991, only about 15 percent was utilized and the rest was discarded. The situation is even more dramatic in the case of gold, where each gram of gold requires blasting and processing about 120 kg of rock—a cube nearly a meter on each side. Overall, the generation of waste rock and smelting residues makes metal mining the industry with consistently the largest rate of release of problematic solid residues.

Table 10.4. Global Materials Flows Associated with Major Minerals, 2000

Mineral	Ore (Tg)	Average Grade (%)	Residues (Tg)
Copper	1580	0.91	1565
Iron	1410	40.0	564
Lead	124	2.5	120
Aluminum	104	23.0	71
Nickel	52	2.5	51
Others	925	8.1	850
Total	4195		3221

Source: After J. E. Young, *Mining the Earth*, Worldwide Technical Paper 109. Washington, DC: Worldwatch Institute, 1992. Some data are from U.S. Geological Survey, *Mineral Yearbook*, Washington, D.C., 2000.

10.4.2 Liquids

Liquids are major residue problems in metal ore extraction and processing. Three categories can be distinguished: mine water, sludge, process chemicals, and tailings.

Mine water is water pumped out of mines to permit ore extraction or remove water that arises from precipitation during mining activities. This water is likely to be acidic and to contain high concentrations of hazardous metals. The acidity arises from reactions of water and oxygen with sulfide ores. For pyrite, for example, the overall reaction can be expressed as:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$

The reaction is mediated by bacteria. Mine water can be pumped to treatment ponds where it is treated and neutralized, but many older facilities do not have this capability in place.

Slurries of gangue, metals, and leaching chemicals are customarily stored in above-ground impoundments and gradually dried to form sludge. This hardened or semi-hardened sludge is generally redeposited back into the exhausted mine cavities. Alternatively, the slurries in their liquid form may be injected directly into exhausted underground mines.

Although process chemicals are used in closed-batch leaching systems, the significant environmental concern is from leaks in the baths. One famous example is that of cyanide, which has escaped the closed bath system in many instances. The cyanide can be transported through surface water systems and have immense deleterious effects on downstream aquatic ecosystems, and in some cases has migrated through ground water aquifers, threatening human drinking water supplies.

Mine tailings pose significant environmental problems years after mining operations terminate. Tailings from heavy metals and coal (Chapter 8) extraction often contain high quantities of toxic heavy metals and acid-forming minerals. Tailings can also contain chemical agents used to process the ores, such as cyanide or sulfuric acid. Tailings are usually stored above ground in containment areas or ponds (and in an increasing number of underground operations they are pumped as backfill into the excavated space from which they were mined). If improperly secured, contaminants in mine waste can leach out into surface and groundwater causing serious pollution.

Unlike the environmental impacts of many industries, which stop when industrial activities stop, liquid mining residues continue to be generated long after mining ceases. Acid mine drainage (AMD) and the drainage of surface and ground water containing toxic metals remain continuing problems in many regions of the world. AMD is likely the mining industry's greatest environmental problem and its greatest liability, especially to waterways. An acid-generating mine has the potential for long-term, devastating impacts on rivers, streams and aquatic life, becoming in effect a perpetual source of pollution. Text box 10.2 illustrates the harmful repercussions of AMD at the Britannia Mine in British Columbia. In addition to being an ecological concern,

AMD has proven to be a significant financial liability. For example, in Canada, there are an estimated 351 millions tons of waste rock from mining, 510 million tons of sulfide tailings, and more than 55 million tons of other mining sources which have the potential to cause AMD. Cleanup at existing acid-generating mines in Canada will cost the mining companies and the government between $2 billion and $5 billion.

Text Box 10.2

Damage from Acid Mind Drainage in British Columbia, Canada

The former Britannia Mine, located 50 km north of Vancouver near Squamish, B.C., was once the largest copper producer in the British Empire. Discovered in the late 1800's, it was operated from 1905 to 1963 by the Britannia Mining and Smelting Company Ltd., and from 1963 to 1974 by the Anaconda Mining Company. In total, approximately 48,000,000 tons of ore were mined from seven ore bodies for copper, silver, zinc, and gold. The mine's mill building is located in the town of Britannia Beach, which sits directly on Howe Sound. The mine extends approximately 6 kilometers westward into the Coastal Mountain Range.

Environment Canada has called the mine "the worst single source of metal pollution on the North American continent." The abandoned mine's AMD currently threatens the health of Howe Sound. Every day, millions of liters of contaminated water from the mine flow into the ocean inlet via Britannia Creek and a large underwater outflow pipe. The resultant effluent is highly acidic, with a pH between 2 and 4, and it carries a whole suite of dissolved metals into Britannia Creek and Howe Sound. These metals include iron, aluminum, cadmium, zinc and copper. During the spring snowmelt, more than a ton of copper, zinc and cadmium can be flushed from the mine's 160km of tunnels and enter Howe Sound in a single day.

In 1996, residents claimed that life in the creek was damaged, and that the mine's toxic water has had a similar effect on aquatic life near the town of Britannia Beach. Surface waters from Britannia Creek are highly toxic to young salmon. When chinook salmon smolts were held in cages near Britannia Creek, they all died in less than 48 hours, whereas at Porteau Cove, a site on Howe Sound that is not impacted by AMD, almost all of the young salmon remained healthy. Studies have shown that the mine effluent is harmful to mussels, brine shrimp and salmon; copper concentrations in Britannia Bay surface waters are well in excess of the toxic level for most marine organisms. By May 1997, it was reported that the only sign of life in Britannia Creek was some algae on rocks.

In April 2001, the first clean-up plan for the Britannia Mine was unveiled. Initial costs of remediation are on the order of $40 million US.

Source: Environmental Mining Council of British Columbia. (http://www.miningwatch.org/emcbc/index.htm)

10.4.3 Gases and Particles

The most significant atmospheric impact of ore extraction is the generation of fugitive windblown dust. Specific sources include ore crushing, conveyance of crushed ore, loading bins, blasting, mine and motor vehicle traffic, use of hauling roads, waste rock piles, windblown tailings, and disturbed areas. Always an annoyance, the dust can be hazardous if it contains arsenic, lead, radionuclides, or other problematic materials. Particulate matter is an environmental concern because it can contaminate air. It can also deposit dust in surface water, causing sedimentation and turbidity.

During smelting, the biggest concern is with the sulfur in the ore. Traditionally, the resulting SO_2 was simply vented to the atmosphere. In modern facilities it is likely to be captured by limestone scrubbing to form gypsum. The gypsum can be used as construction filler or in wallboard manufacture if geographical proximity makes these uses financially attractive.

During the refining step, the gaseous emissions of most concern are probably the saturated fluorocarbons (CF_4 and others) from the electrolytic refining of aluminum. (The saturated fluorocarbons are potent greenhouse gases.) Vigorous efforts are underway to reduce these emissions.

10.4.4 Land Use and Habitat Destruction

By its very nature, mining can cause large disturbances to the land. The large amounts of land required for metal ore extraction, particularly strip mining, result in significant deforestation and habitat destruction. Not only can there be direct terrestrial and aquatic ecological impacts from mining, but the manipulation of topography and releases of particulates and chemicals can all have indirect impacts on various habitats.

Sedimentation and erosion due to mining activities pose serious problems. The extent of erosion and sedimentation depends on various factors, including the degree to which the surface has been disturbed, the prevalence of a vegetative cover, the type of soil, the slope length, and the degree of slope. Disturbed areas with little or no vegetative cover, soils high in silt, or a steep slope are the areas most likely to erode. Erosion and sedimentation affect surface water and wetlands more than any other media. Erosion can also adversely affect soil organisms, vegetation, and revegetation efforts because it results in the movement of soil, including topsoil and nutrients, from one location to another.

Mining subsidence is also an environmental concern. Subsidence is the surface impact of the collapse of overlying strata into mined-out voids. Subsidence may manifest itself in the form of sinkholes or troughs. Sinkholes are usually associated with the collapse of a portion of a mine. Sinkholes or depressions interrupt surface water drainage patterns, affecting ponds, streams, and wetlands. Reducing the withdrawal of groundwater through specific practices such as recycling mine water can reduce

the potential for subsidence. The threat and extent of subsidence is related to the method of mining employed. In many instances, traditional room and pillar methods of underground mining leave enough material in place to avoid subsidence. However, high volume extraction techniques, such as pillar retreat and longwall mining, result in a strong likelihood of subsidence. Preventing subsidence involves leaving support mechanisms (e.g., pillars) in place after completing the mining operation or backfilling with waste rock.

A final land use concern from mining is aesthetic degradation of mined landscapes. Aesthetics involve the general visual environment, including the overall scenery and unique topographical characteristics. Since most mining operations result in large land disturbances, aesthetic impacts can be significant. Recontouring the land to reduce unnatural anomalies, backfilling holes, revegetating, and promoting wildlife habitats can all improve the aesthetics of mining operations.

10.4.5 Sustainability Assessment

The potential emittants resulting from processes in this industrial sector are given in Table 10.5, and the potential hazards are collected and evaluated in Table 10.6. Only the usual engineering metals are included, and those only if they are the principal target constituent of the ore. The highest concern is for mine water, tailings, lead, and mineral acids. The potential hazard from dissipated copper and silver, sulfur dioxide, slags, and discarded overburden is also high. The results appear in the throughput-potential hazard diagram of Figure 10.7.

The resource scarcity concerns in this sector are also diagrammed in Figure 10.7. Of particular note are four metals with rather short depletion times: copper, gold, silver, and zinc.

This sector uses very large amounts of both energy and water. As a result, the PEC and PWC matrices both have the "high concern" row called out for special attention in Figure 10.8.

Table 10.5. Processes, Activities, and Potential Emittants for the Metal Ore Extraction and Processing Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Mining	Mine water
	Stripping	Overburden, habitat loss
Beneficiation	Crushing, grinding	Windblown dust
	Floatation	Toxic tailings
	Leaching	Toxic tailings
Cleaving bonds	Smelting	SO_2, H_2SO_4
Purification	Refining	Slags, CF_4

Table 10.6. Throughput-Hazard-Scarcity Binning of Materials in the Metal Ore Extraction and Processing Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Site preparation	M	Ecosystem	M	–
Overburden	H	Ecosystem	M	–
Aluminum	H	–	L	L
Copper	H	Ecosystem	M	H
Gold	H	–	L	H
Iron	H	–	L	L
Lead	H	Human	H	H
Nickel	H	–	L	M
Silver	H	Ecosystem	M	H
Zinc	H	–	L	H
Mineral acids	H	Ecosystem	H	L
Mine water	H	Ecosystem	H	–
Windblown dust	M	–	L	–
Tailings	H	Ecosystem	H	–
Slags	M	Ecosystem	H	–
SO_2	M	Acid rain	H	–
CF_4	L	Climate change	H	–

The sector ΣWESH plot in Figure 10.9 is dramatic in its concentration of entries to the right of the diagram, and especially to the upper right. It is obvious that the potential for poor environmental performance in this sector is great, and that continued efforts to reduce the magnitudes of inputs and losses will pay great dividends.

10.5 SECTOR PROSPECTS

10.5.1 Trends

Trends for the metal ore extraction and processing sector have been divided into extraction and mine site trends and processing trends, reflecting the two main operations within this industry. Regulation and societal trends significant to this sector are also discussed.

10.5.1.1 Extraction and Mine Site Trends

The increasing use of high technology during both exploration and extraction processes is an active trend for the mining industry.

A major effort is the development of techniques for non-invasive exploration using remote sensing, advanced data processing, and computer modeling techniques that more accurately locate and map areas of minable resources. To the degree that

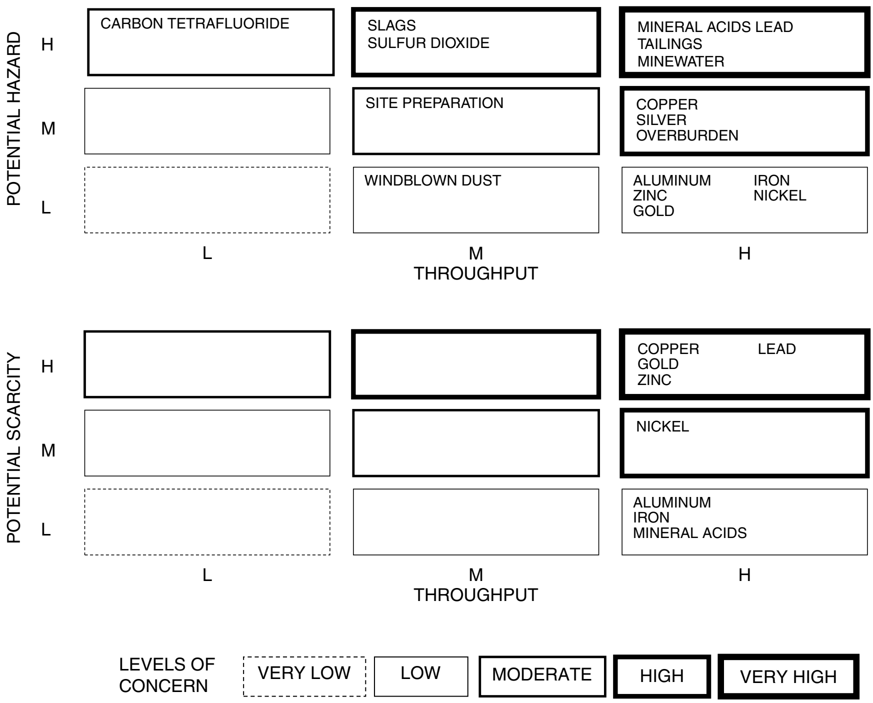

Figure 10.7. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the metal ore extraction and processing sector.

this is successful, it could minimize the drilling of test holes and, by mining higher-grade ores, the generation of overburden. One example is the development of real-time mineral content sensors for all minerals. This would minimize the energy-intensive and laborious processes of collecting samples (surficially and sub-surficially) and analyzing them. Another more distant example is the creation of new sensors operating from space, high altitudes, low altitudes, above ground, and below the ground surface to characterize mineral occurrences. Techniques like this would reduce the need for blind drilling and exploration.

Once a mine has been opened, a second potential new technology can be envisioned. Known as near-face beneficiation, this is conceived as the development of processes by which ore removed from the mine face (i.e., the exposed rock in the strip mine or shaft) could be beneficiated and perhaps further processed within the mine itself rather than by the removal of the entire rock volume from the mine to a designated processing area. The challenge will be to develop physical and chemical separation processes that can be carried out efficiently in rather small spaces, while maintaining the desired level of product purity and worker safety. Given the enormous

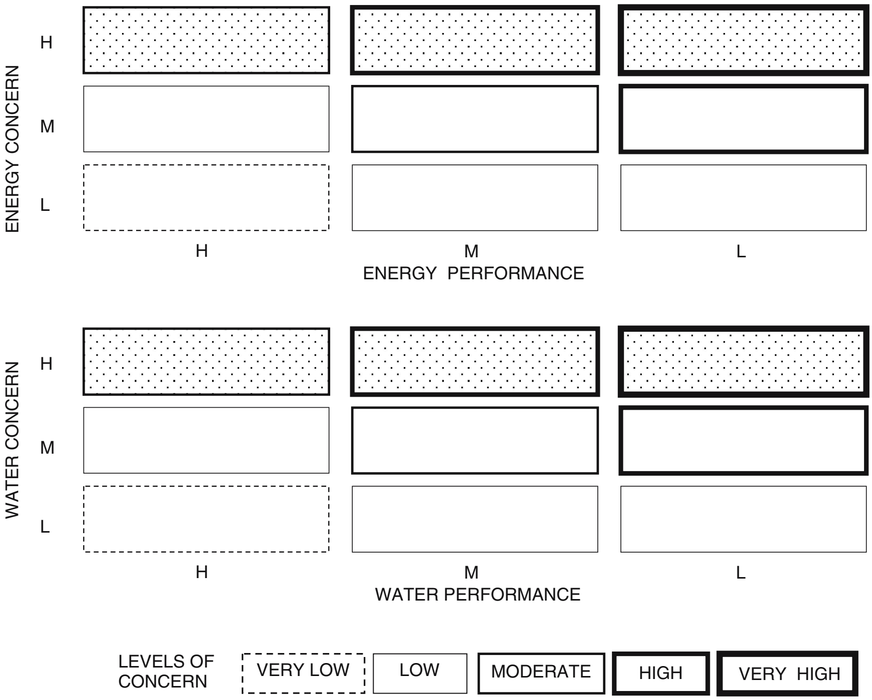

Figure 10.8. The energy performance-energy concern matrix (top panel) and water performance-water concern matrix (bottom panel) for the metal ore extraction and processing sector. The stippled rows reflect typical levels of sector consumption.

amounts of overburden involved, the environmental improvement potential for near-face beneficiation is high.

Research is underway in the mining engineering field to develop robot miners—robots directed by sophisticated navigational and chemical sensors—that could tunnel into promising ore bodies and efficiently extract rich metal ore from small veins and thin seams of high-quality material. The extraction process itself might make use of biological extraction, aspects of which are currently used for above-ground ore processing. Similar approaches could then be applied to underwater mining of manganese nodules and other marine and freshwater subsurface resources.

10.5.1.2 Processing Trends

A major effort is being made to reduce the amount of energy used in metals refining. Current levels are between two and three times the predicted thermodynamic minima, and comprise more than 3 percent of total industrial energy use. Better

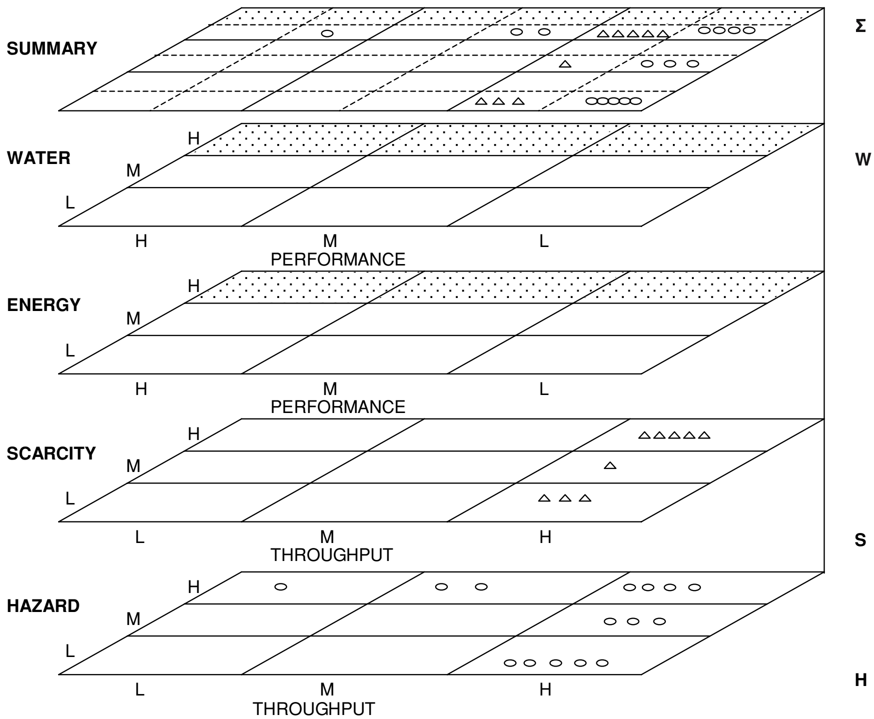

Figure 10.9. The ΣWESH plot for the metal ore extraction and processing sector. The squares and circles refer to the materials in Figure 10.7.

energy housekeeping and the gradual phase-in of more efficient equipment will make noticeable improvements. As long as low-grade ore is mined and metal is melted, however, the energy requirements will continue to be substantial.

In smelting and refining, the long-term goal is for zero or near-zero emissions. Two factors strongly influence achievement of this goal. The first is that downstream emissions reflect the purity of the material provided by the upstream processes. If the products of extraction can be made purer, slag and other unwanted byproducts of smelting and refining will be decreased. The second consideration is that many metals occur as sulfides in the ore (Table 10.1). If near-zero emissions are to be achieved in smelting, the sulfur must be trapped; it cannot be avoided, as it is part of the feed stock material.

Technology under development will help reduce emissions of carbon dioxide and other greenhouse gases from aluminum smelting. Today, primary aluminum processing typically involves a carbon anode with molten cryolite as the electrolyte and molten aluminum acting as the cathode in an electrolytic cell. When electric energy

is added and the carbon anode consumed, the raw alumina (Al_2O_3) is converted to aluminum plus CO_2. Additional variability in the process causes the emissions of perfluorocarbons, which are greenhouse gases. Development of inert cathode and anode technology for *electrowinning* of aluminum in primary electrolysis cells is the subject of ongoing research. This technology would significantly decrease emissions of gases that contribute to global climate change.

Two process trends specific to the iron and steel manufacturing industry are of interest. First, the sintering process of ironmaking has the capacity to recycle and recover iron-bearing waste oxides that are generated from ironmaking and steelmaking facilities. It has an added benefit of producing a material that replaces iron pellets with recycled and iron-bearing secondary material, and also adds stability to blast furnace operation. Some blast furnaces in Japan operate on virtually 100% sinter feed. This emphasis on recycling and recovery will likely become a more common trend in the ironmaking industry. It should be noted that other environmental concerns from sintering, primarily water and air effluents, pose significant environmental concerns. These environmental concerns and high overall capital and operating costs have led to declining use of traditional sinter plants. This has afforded the emergence of other waste oxide agglomeration processes that serve as a substitute for sintering.

Second, the steel industry is starting to use natural gas to reduce iron ore to produce Direct Reduced Iron (DRI). As direct reduction plants are not built on the same, enormous scale as blast furnaces, their investment costs are lower, and they have been mainly constructed in developing countries where natural gas is relatively inexpensive. Recently, however, even in developed countries, direct reduction plants are drawing more and more attention as a way to provide a stable supply source of both pure and scrap iron. This process is environmentally superior because it recycles the used gas for a second combustion, making the energy consumption more efficient and less polluting than traditional blast furnace processes.

10.5.1.3 Social and Regulatory Trends

In the U.S., since the passage of the Resource Conservation and Recovery Act (RCRA) in 1976, Congress, the mining industry and the Environmental Protection Agency (EPA) have maintained that waste products generated by the mining industry do not warrant hazardous waste regulation. At sites where hazardous substances may have been released due to mining operations, the Comprehensive Environmental Response, Compensation and Liability Act (better known as Superfund) sometimes comes into play. It provides for emergency response cleanup and determination of liability for hazardous substances released into the environment, including releases from inactive waste disposal sites.

As significant problems like acid mine drainage and land and habitat impacts can persist far beyond the long life of a mine, it is likely that there will be increased social and regulatory pressure brought to bear on mining operations to avoid and reduce such impacts.

Text Box 10.3

Curbing Greenhouse Gas Emissions from Iceland's Steel Industry

The silicon used in silicon-bearing steels is produced in a reaction that can be described as

$$SiO_2 + 2C \rightarrow Si + 2CO$$

Similarly, a side chain reaction in aluminum production is

$$Al_2O_3 + 3C \rightarrow 2Al + 3CO$$

The toxic CO gas is traditionally converted to CO_2 (a greenhouse gas) by adding ambient air.

To minimize Iceland's CO_2 emissions, researchers from the University of Iceland are working with local industry to produce methanol (CH_3OH) from the CO and from hydroelectrically-generated hydrogen:

$$CO + 2H_2 \rightarrow CH_3OH$$

The methanol that is produced can be used as fuel for Iceland's transport and fishing industries, and CO_2 emissions from methanol-fueled vehicles are about half those of an equivalent gasoline-fueled vehicle. Thus, if the approach is fully implemented, it appears possible to reduce the country's CO_2 emissions by between one-third and one-half.

Source: B. Arneson and T. Il. Sigfusson, Converting CO_2 emissions and hydrogen into methanol vehicle fuel, *JOM, 51*(5), 46–47, 1999.

10.5.2 Possible Future Scenarios

10.5.2.1 Trend World

In this scenario, virgin material would be extracted from lower and lower grades of ore as overall reserve quality decreases. However, pressure would continue to be placed on mining companies to reduce and mitigate environmental damage. Recycling will likely become more and more prevalent as virgin supplies become more costly to extract and process.

The potential to pollute is clearly large in the metal ore extraction and processing sector, and will continue to be so in the future, under this scenario. The demand for metal products, however, will continue unabated. Substantial supplies of metals will be needed to support the evolution of a technological society. Even those metals that are needed in small quantity may be essential for certain functions. Examples include the alloying elements in high-strength steels and the platinum-group metals used as catalysts in many industrial chemical reactions.

10.5.2.2 Green World

In this scenario, improved environmental technologies will continue to be developed for the metal mining sector. Among them will be improved chemical management of tailings, the development of non-toxic reagents for some leaching processes, and the use of wetlands systems for treating acid mine drainage.

A sharp decrease in the mining of metal ores will occur because of the declining economic feasibility of extraction and the rising costs associated with adequate mitigation of environmental impacts. Metals will continue to be important materials in industry and commerce, but they will increasingly be derived from scrap metal. New technologies will be developed to enable the recovery of metals from complex products, and infrastructure will be put in place to collect used products containing metals.

10.5.2.3 Brown World

In this scenario, the response to declining high-grade ore reserves will involve intensification of mining activities to extract lower-grade ore. To acquire the same amount of metal, more ore will be mined and more overburden, gangue, and tailings will result. The area of land required to extract the lower grade ore will increase, likely infringing upon previous untouched ecological habitats across the globe. Energy efficiency measures will not improve during extraction, resulting in increased greenhouse gas emissions from this process.

The ore processing trend in this scenario continues to resort to high energy consumption and low utilization rates of recycled materials, such as are used in the EAF. With expanded production of low-quality ore, the energy requirements of processing will likely increase as well.

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